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A Preliminary Report on Doppler Radar Observation of Turbulence in a Thunderstorm

RALPH J. DONALDSON, JR.

OFFICE OF AEROSPACE RESEARCH
United States Air Force

AFCRL-67-0015
JANUARY 1967
ENVIRONMENTAL RESEARCH PAPERS, NO. 255

METEOROLOGY LABORATORY PROJECT 6672
AIR FORCE CAMBRIDGE RESEARCH LABORATORIES
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Abstract

Vertical-incidence observations by Doppler radar of velocities in a thunderstorm reveal some regions in which the spread of velocities is unusually broad. The widths of the vertical velocity spectra are generally greatest along the edges of a major updraft, where the maximum shear in updraft speed also occurs. The observations indicate that turbulence is an important cause of the abnormally wide velocity spectra, and suggest the utility of Doppler radar measurements of the vertical velocity spectrum as an indicator of severe cloudy-air turbulence. Furthermore, vertical velocity spectra in the more convective regions of thunderstorms, where they may be seriously affected by turbulence and wind shear, probably give an exaggerated picture of the particle size distribution.

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A Preliminary Report on Doppler Radar Observation of Turbulence in a Thunderstorm

1. INTRODUCTION

The measurement by Doppler radar of vertical velocities of precipitation is an attractive mode of observation, requiring a fixed vertical beam with no necessity to record and process antenna orientation. In stratiform precipitation, where vertical air motion is but a small fraction of particle fall speeds, this method provides an opportunity to sample precipitation size distributions throughout the height of a storm, using relationships of particle size with fall speed. In convective storms, however, in which the magnitudes of air motion and precipitation descent relative to the air are comparable, Doppler radar measurements with a fixed vertical beam are ambiguous. Simplifying assumptions are necessary to analyze the observed velocities into their component parts. One assumption which is sometimes adopted is that turbulent velocities are small compared with the spread of precipitation fall speeds. This report questions the validity of such an assumption in thunderstorms.

The discussion is concerned with measurements of only one thunderstorm, and is, for that reason, necessarily of a preliminary nature. The thunderstorm was observed on 19 August 1965 with a C-band Doppler radar located at Bedford, Massachusetts. An earlier report (Donaldson, Armstrong, and Atlas, 1966)

(Received for publication 9 January 1967)

described the variation with azimuth of mean horizontal velocity in a line of storms when the nearest storm was 20 miles distant. Later, when one of the thunderstorms passed over the radar, the antenna was pointed vertically. Velocity information was recorded on analog magnetic tape in 10 adjacent range gates, spaced 1 μsec apart, for a period of 3 seconds, followed by a jump of the set of range gates to the next higher altitude. In this manner the storm was sampled from a height of 1.5 km to 15 km once every 27 seconds. The analyzed observations cover a duration of 17 minutes in which rainfall was very heavy but no hail was reported anywhere on the ground.

A 100-element filter bank was used for frequency analysis of the Doppler signal, and the spectra of vertical motion were converted to digital form. Groginsky (1966) has discussed the methods for processing the spectral data. The basic parameters which were computed for each power-velocity spectrum were total received power (later converted to reflectivity), mean velocity, and standard deviation.

2. OBSERVATIONS

The basic observations in the time-height domain are portrayed in Figures 1 and 2. The shaded bands of radar reflectivity factor Z in Figure 1 are in conventional units of mm^6/m^3. The contours of $\overline{V}$ represent the field of mean reflectivity-weighted vertical component of Doppler velocity, and the numbers give values in m/sec. Positive or rising contours are solid, negative or falling ones are dashed, and the balance contours, or $\overline{V} = 0$, are located by the railroad tracks. This diagram is identical with Figure 3 of Donaldson et al. (1966).

Figure 2 is a measure of the spread in vertical velocities, expressed as σ_v or standard deviation in m/sec. The values were computed from the most intense 20-dB portions of the output of the spectrum analyzer. Where $\sigma_v = 2$ m/sec or higher the contours are solid lines, and areas enclosed by $\sigma_v > 3$ m/sec are shaded.

3. ESTIMATION OF VERTICAL MOTIONS

The field of vertical motion in the observed time-height plane was inferred by two methods and compared. In the modified-Rogers technique the mean reflectivity-weighted particle fall speed $\overline{V}_f$ is estimated by means of some relationship with reflectivity. Then, since the observed Doppler velocity is the sum of the particle fall speed and air motion, the latter is determined. Rogers (1964) derived a relationship between Z (mm^6/m^3) and $\overline{V}_f$ (m/sec) based on an exponential distribution of raindrop numbers with size (see, for example, Marshall and Palmer, 1948) and a simple approximation (Spilhaus, 1948) to the relation between raindrop size and

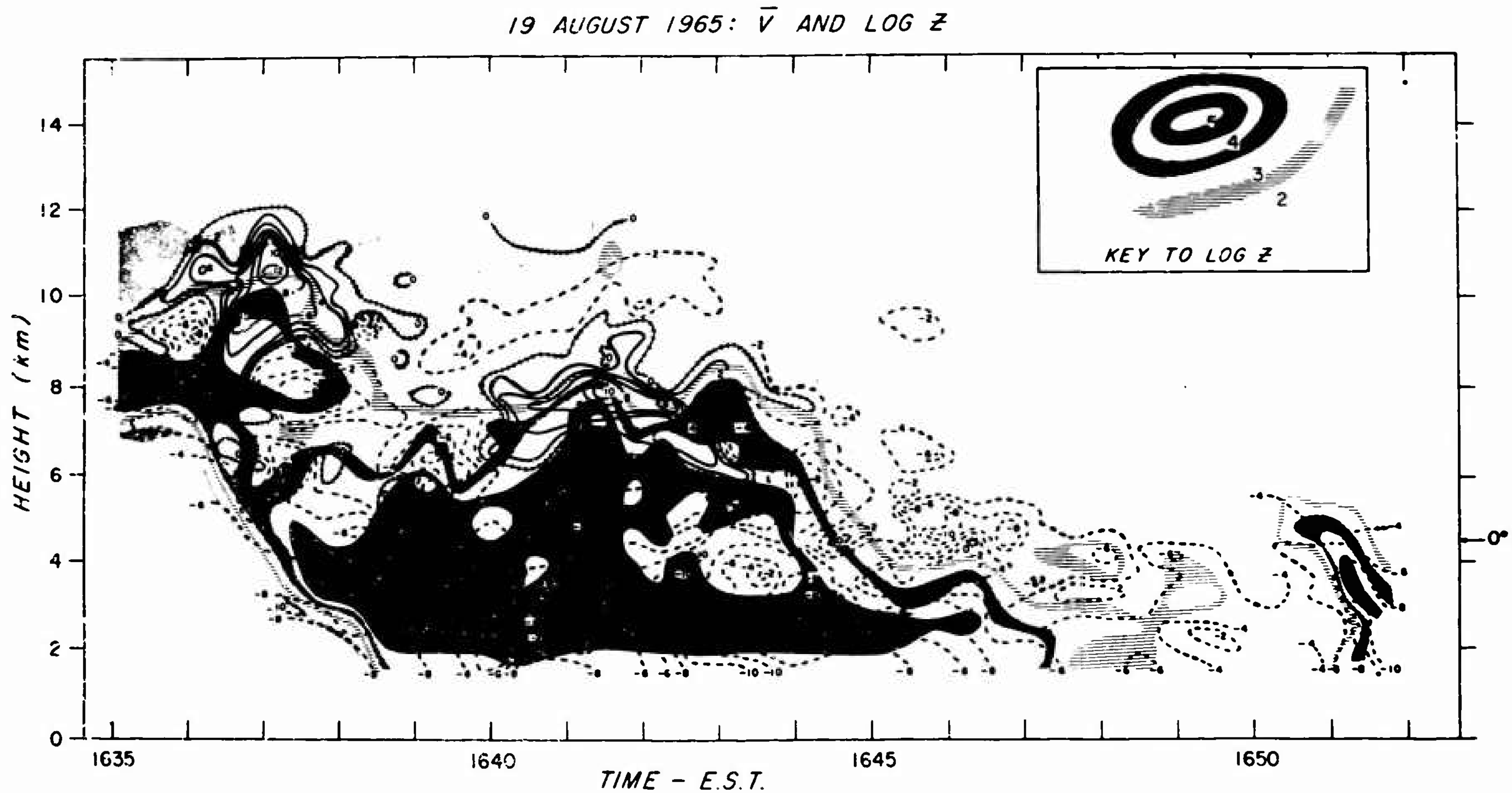

Figure 1. Superposition of Time-Height Fields of Reflectivity (see key to shading) and Mean Vertical Doppler Velocity (m/sec, positive upward) During Overhead Passage of the Thunderstorm of 19 August 1965. The Doppler radar was located at Bedford, Massachusetts, and the antenna beam was in a fixed vertical position. Dashed lines denote downward motion, solid lines upward motion, and railroad tracks zero vertical velocity

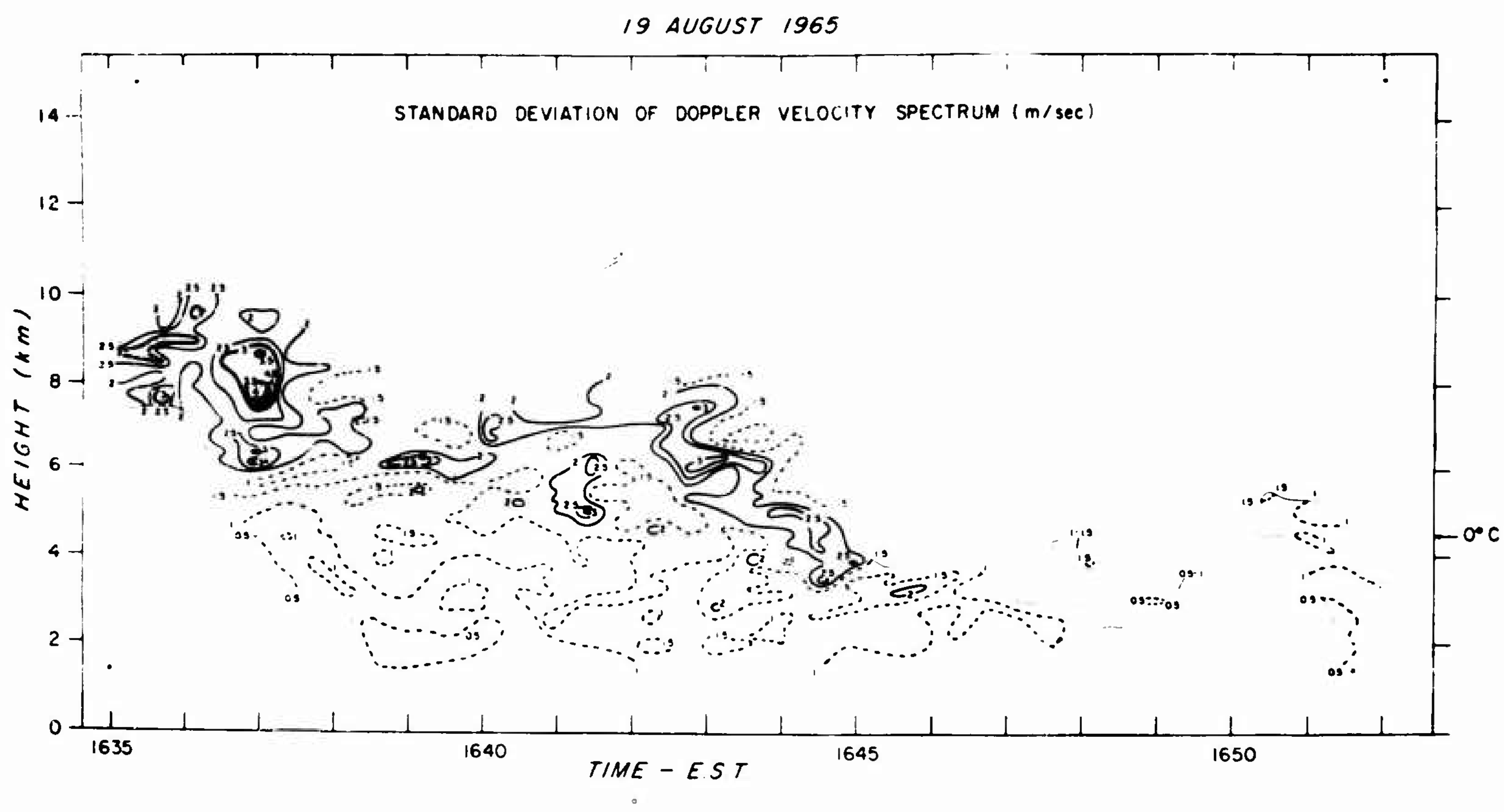

Figure 2. Time-Height Field of the Standard Deviation, in m/sec, of the Vertical Doppler Velocity Spectrum of the Thunderstorm Depicted in Figure 1. Heavy solid lines define standard deviation contours of 2 m/sec or larger, and shaded areas point out regions where standard deviation exceeds 3 m/sec. Very thin, solid boundary lines are reflectivity contours of $Z = 10^3\ mm^6/m^3$

fall speed: $\overline{V}_f = 3.8\ Z^{1/14}$. The modified Rogers method used here conveniently but crudely estimated vertical air motion by the simple expedient of setting $\overline{V}_f = 2 \log Z - 2$, restricted, of course to regions where $Z > 10$ since we are not prepared to consider precipitation which ascends relative to the air. The resulting field of updrafts and downdrafts is depicted in Figure 3, which is identical with Figure 4 of Donaldson et al. (1966).

Figure 4 shows the field of vertical air motion inferred according to a modified Battan method. Battan (1964) and Battan and Theiss (1966) derived updrafts and downdrafts in Arizona thunderstorms by assuming that the slowest falling (or fastest rising) particles observable with their vertically-pointing Doppler radar would have a fall speed of 1 m/sec in still air. In other words, they considered that the upper bounds of their velocity spectra, where the received power density disappeared into noise, represented either ice crystals or drizzle drops. Turbulence would broaden the observed spectra and lead to an overestimate of updraft speeds, but Battan and Theiss, drawing on Atlas (1964) for support, asserted that the uncertainties in their method caused by turbulence are in the order of only ± 1 m/sec. The modified Battan technique used to obtain Figure 4 assumed that fall speeds of 1 m/sec were given by the upper intersection of the velocity spectrum with a power level 10 dB below the maximum power. This modification was necessary because of the poor response for weak signals of the Rayspan filters used for spectral analysis. At moderate to high values of reflectivity the noise level is considerably more than 10 dB below the maximum power level, and so our modified Battan method would provide smaller estimates of updraft velocity than the technique actually used by Battan and Theiss. These two techniques are illustrated by the sketch of Figure 5.

A comparison of Figures 3 and 4 reveals a similarity in the general pattern of updrafts inferred by both methods. In each case there is a core of maximum updraft just inside the leading (left) edge of the storm at an altitude of about 10 km, and another major updraft center deeper into the storm at a slightly lower height. There are, however, minor differences in pattern as well as in magnitude. These differences are noted in Figure 6 on the same time-height scale used for the previous diagrams. The difference in inferred updrafts, ΔW, is positive where the modified-Rogers updraft exceeds the modified-Battan updraft. Positive numbers on Figure 6 tend to occur where reflectivities are high and negative numbers appear where the spread of velocities is great.

We may imagine how Figure 6 might look if it had been possible to follow the Battan and Rogers methods more faithfully. A correction for the inadequacy of the 10-dB upper spectral bound in comparison with Battan's technique would increase updrafts (or decrease the magnitude of downdrafts) everywhere, but particularly in the region of highest reflectivities. The correction is in the direction

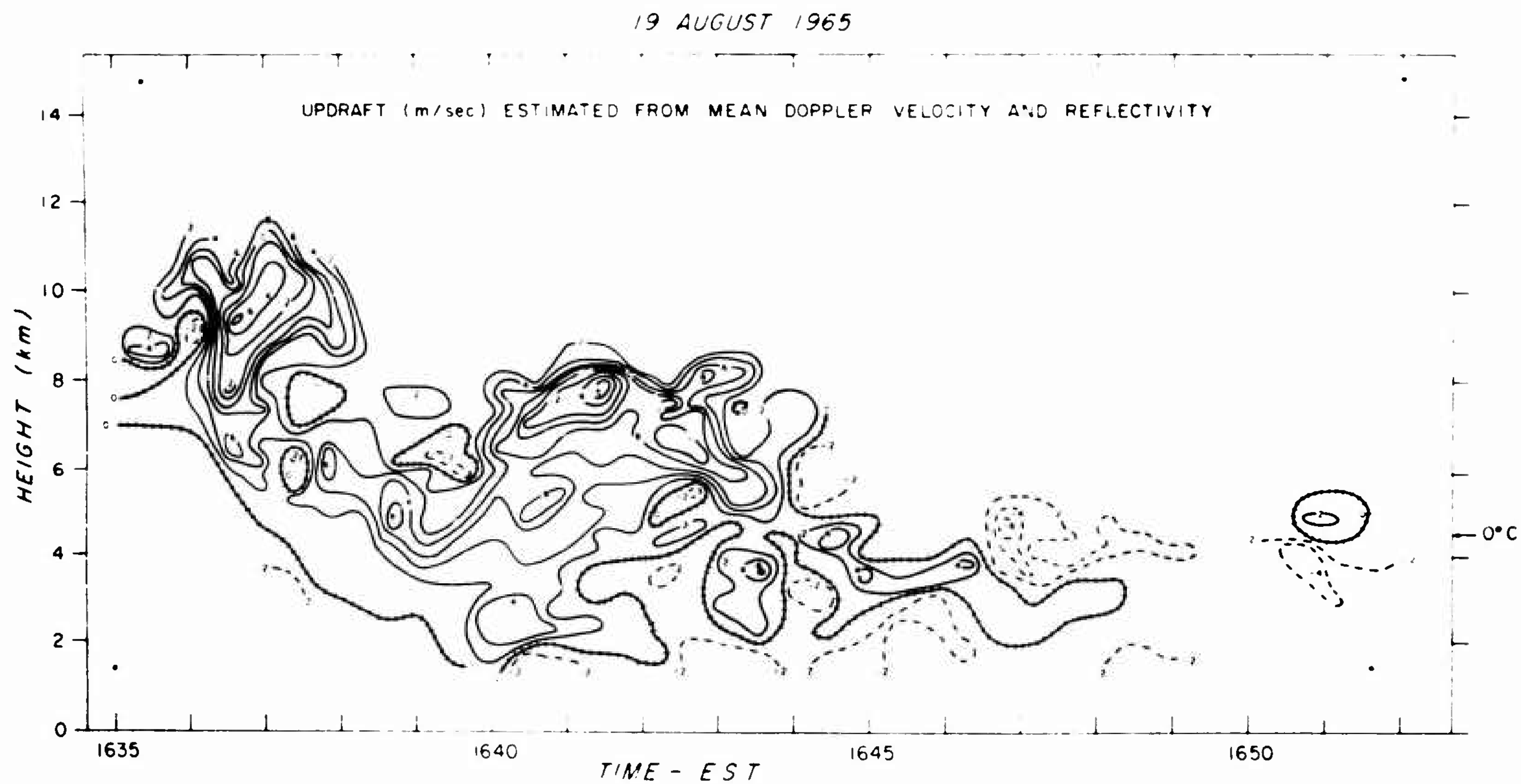

Figure 3. Vertical Air Motion Field in 19 August 1965 Thunderstorm, Estimated from Mean Doppler Velocity and an Assumed Relationship Between Reflectivity and Mean Particle Fall Speed (see text). Updrafts are solid contours, and downdrafts are dashed contours, with railroad tracks showing locations of zero vertical air motion

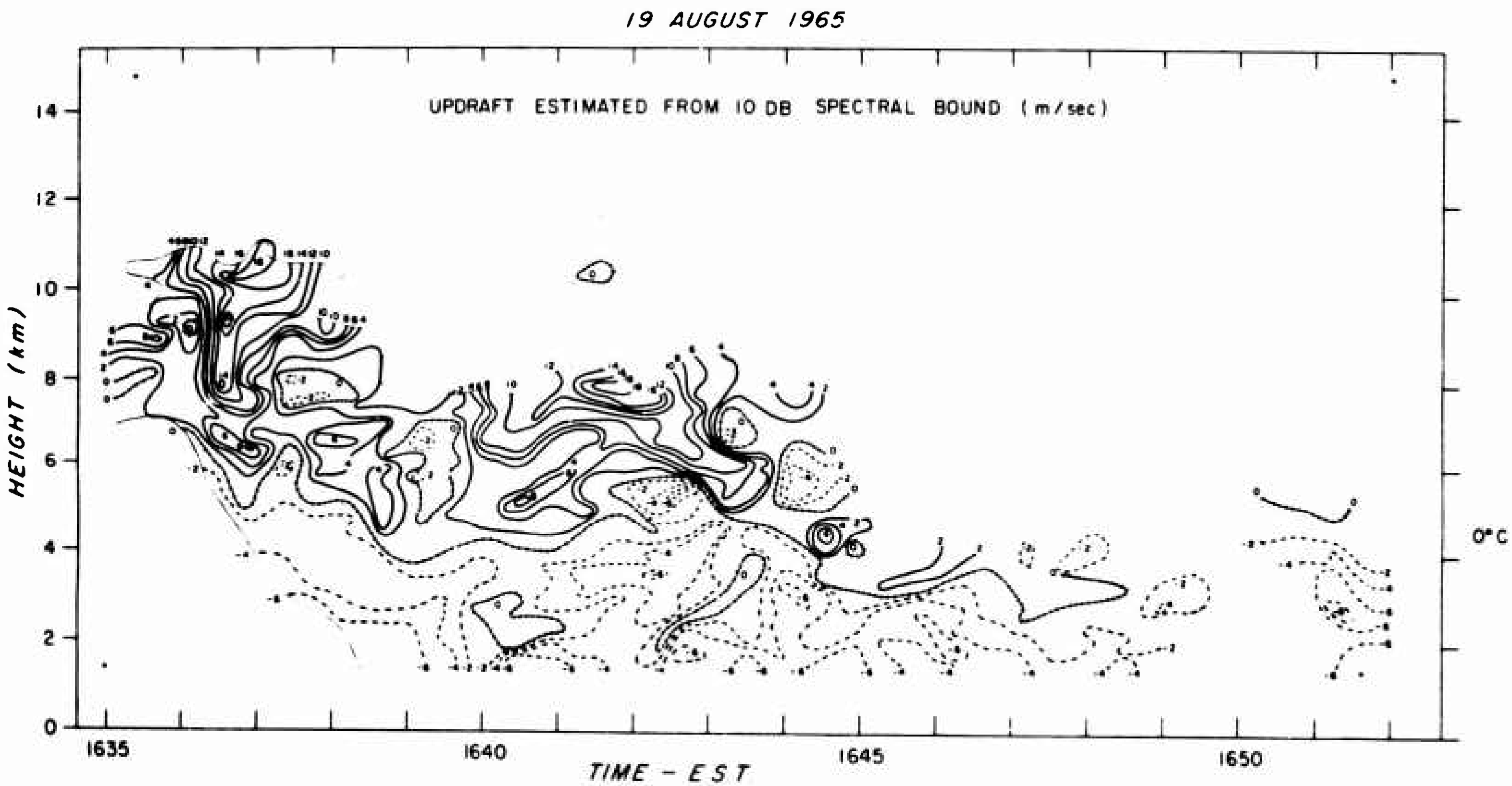

Figure 4. Vertical Air Motion Field Estimated by Assuming that 10-dB Upper Bound of Vertical Velocity Spectrum Indicates the Motion of Particles Which Would Descend with a Speed of 1 m/sec in Still Air. Contour designation is the same as Figure 3

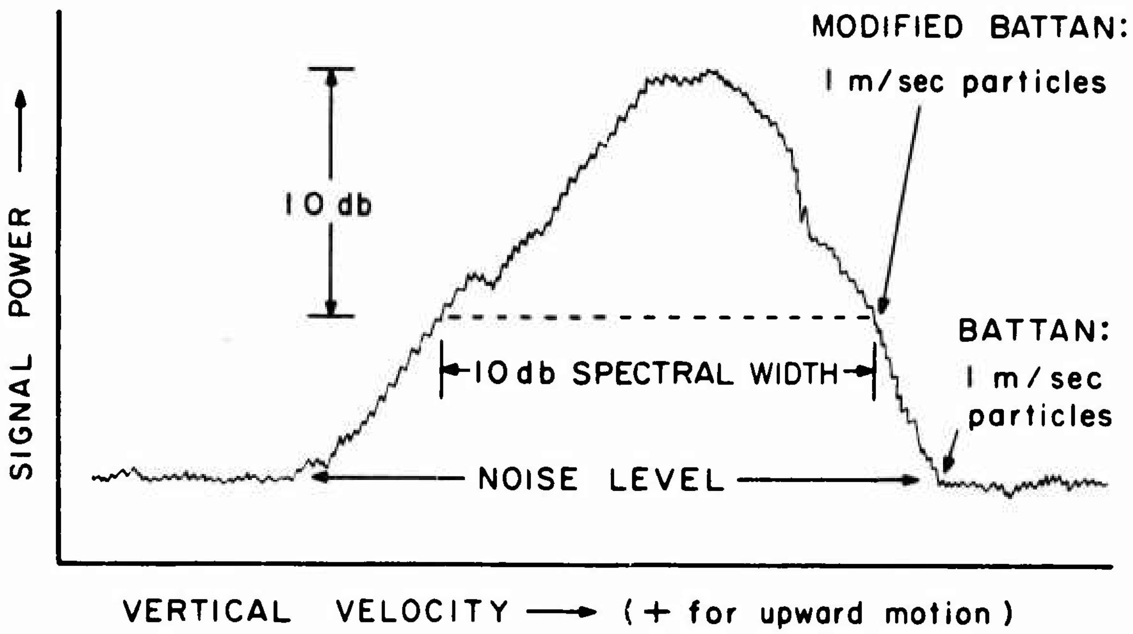

Figure 5. Schematic Illustration of the Technique of Estimating Vertical Air Motion by Consideration of the Spread of the Vertical Velocity Spectrum. The modified Battan method was used to derive the updrafts and downdrafts illustrated in Figure 4

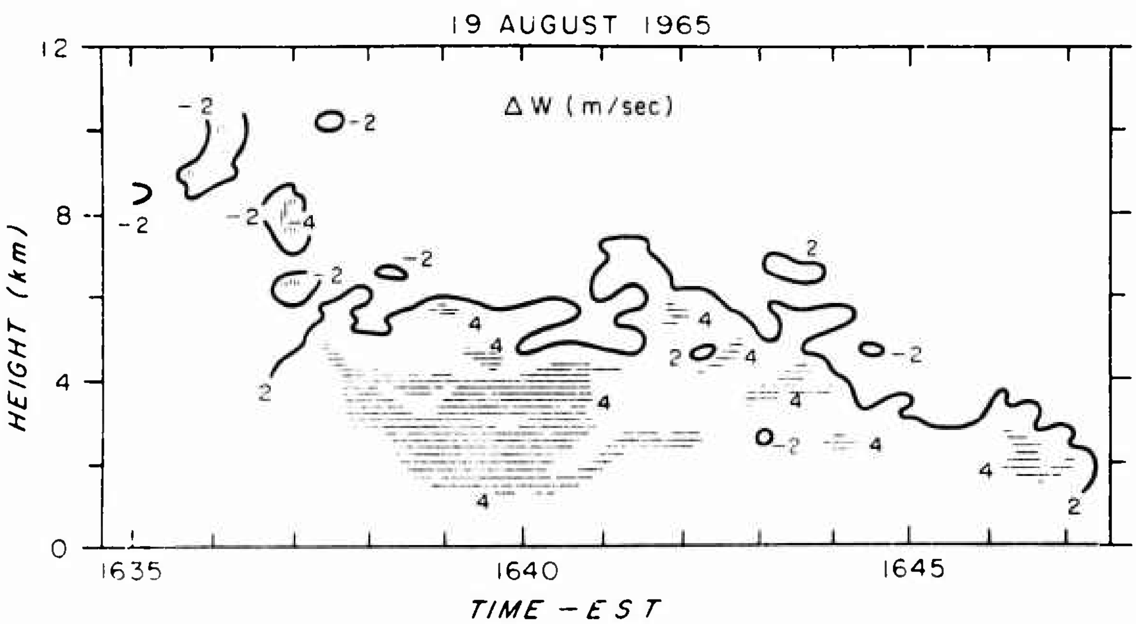

Figure 6. Time-Height Field of Differences Between the Two Methods of Estimating Vertical Air Motion, Given by Subtracting the Contours of Figure 4 from Those of Figure 3. Shaded areas show regions where the magnitude of the difference exceeds 4 m/sec

of diminishing ΔW. Such a correction would probably eliminate most, if not all, of the horizontally hatched areas below 4 km where $\Delta W > 4$ m/sec, but at the same time it would substantially enlarge the vertically hatched areas at the leading edge where $\Delta W < -4$ m/sec.

The modified Rogers method appears to be a good approximation to Rogers' scheme in the area of high reflectivity and temperatures warmer than 0°C. In the region of moderate reflectivity, however, at the leading edge of the storm, which is well above the 0°C level, a better estimate of the mean particle fall speeds would be, perhaps, several m/sec higher than the modified Rogers scheme, thereby increasing ΔW in this place almost as much as correction toward the Battan technique reduced ΔW. The final, corrected ΔW picture would be flattened out, except for rather small areas high up near the leading edge of the storm where negative values of ΔW would be about as prominent as they are in Figure 6. In these areas the width of the velocity spectrum is inappropriately large.

4. CONTRIBUTIONS TO SPECTRAL WIDTH

The distribution of spectral widths of the vertical velocity across the entire time-height plane of Figures 1 to 4 is displayed in Figure 7. The 929 spectra are plotted in two ways: 10-dB width (abscissa) and standard deviation or σ_V (ordinate). (The 10-dB spectral widths are discontinuous because of the discrete nature of the filter bank used for spectral analysis.) If a particular spectrum has a Gaussian distribution, the ratio between its standard deviation and its 10-dB width would fall on the straight line marked "Gaussian." The great majority of the spectra appear to be quite close to this Gaussian criterion, with the exception of a few extremely broad spectra having 10-dB widths in excess of 16 m/sec. The median value of σ_V is 1.4 m/sec; in 20 percent of the spectra $\sigma_V > 2$ m/sec, and $\sigma_V > 3$ m/sec for 3.4 percent of the cases.

Now why are some of the spectra so broad? This interesting question was also faced by Battan and Theiss, because they measured maximum spectral widths of the same order as those plotted on Figure 7. Assuming reasonable confidence in the measurements, there are just two answers: a broad distribution of precipitation fall speeds which might be expected with hail, or broadening of the spectrum by turbulence and shear. Of course, both causes could be contributing to the same effect.

An examination of the correspondence of spectral width with other parameters of the vertical velocity spectrum is given in Figures 8 and 9. The ordinate on these figures is spectral variance or σ_V^2. An indication of a correlation, or lack of it, with inferred updraft and reflectivity (Figure 8) and shear of the updraft (Figure 9)

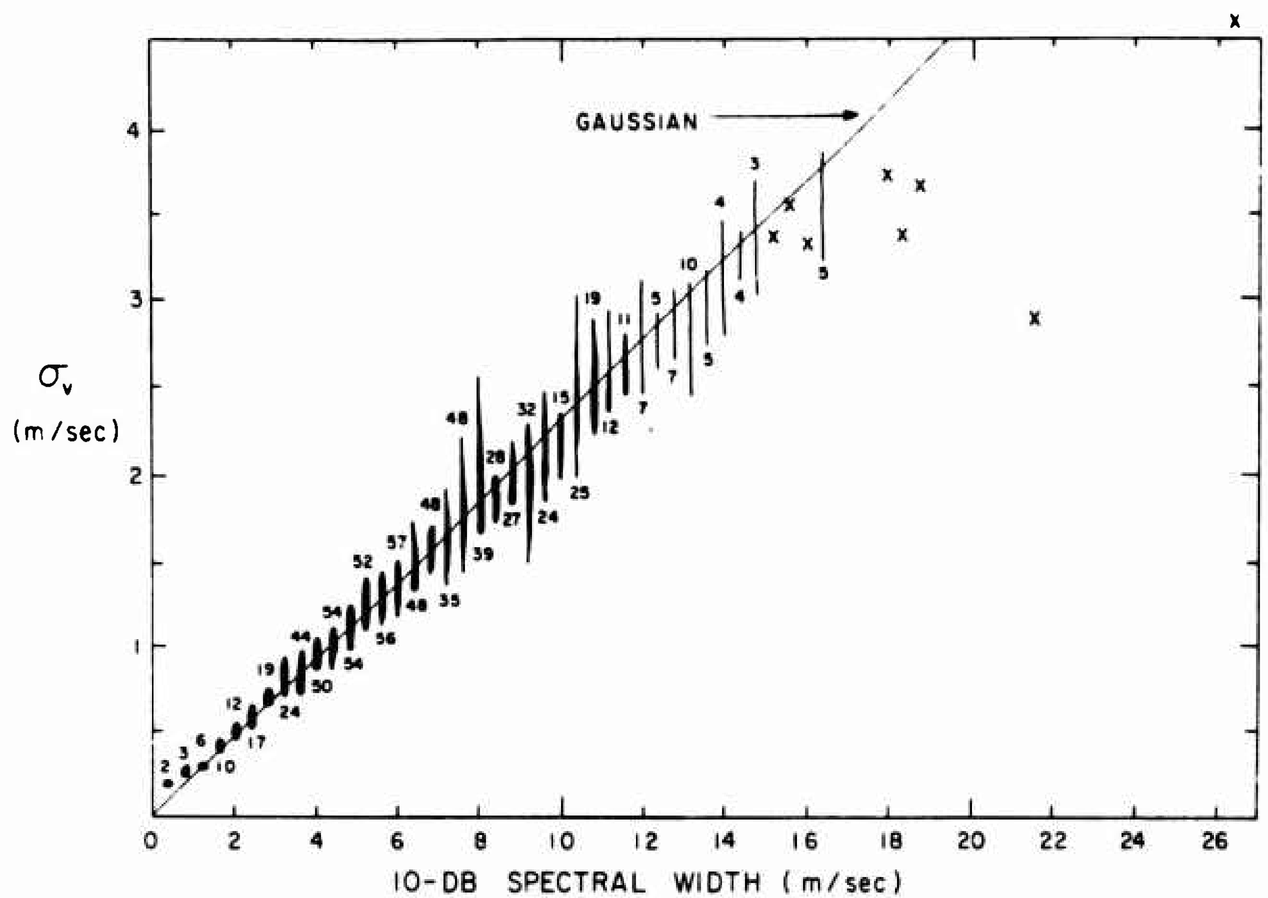

Figure 7. Distribution of Widths of the Velocity Spectra Measured in the 19 August 1965 Storm, Plotted as Standard Deviation Versus Spread of Velocities Within 10 dB of the Peak. The data are grouped in discrete categories of 10-dB width in accordance with the resolution of the filter bank used for spectral analysis. The numbers of spectra in each category are noted beside vertical lines which show the range of standard deviations within each category of spectral width

is indicated by grouping the variance into seven categories: 0 to 1, 1 to 2, 2 to 3, 3 to 4, 4 to 5, 5 to 6, and > 6 m^2/sec^2. Within each variance category median or mean values of the other parameters are plotted.

The right part of Figure 8 shows a slight negative correlation of spectral variance with reflectivity. The median Z of spectra with σ_v^2 between 1 and 2 m^2/sec^2 is 8 dB higher than the median Z where σ_v^2 exceeds 6 m^2/sec^2. This is contrary to the expectation of Rogers (1964) for the fall speed characteristics of rain, where larger drop sizes mean an increase of both Z and spread of fall speeds. On the other hand, Battan (private correspondence) reported a good positive correlation between spread of the vertical velocity spectrum and reflectivity in two Arizona storms. One of these storms was discussed by Battan and Theiss (1966).

The left half of Figure 8 shows a good correlation of variance (except for values above 6) with updraft computed according to the modified Rogers method. The Rogers method for estimating updraft was used here because it is independent of

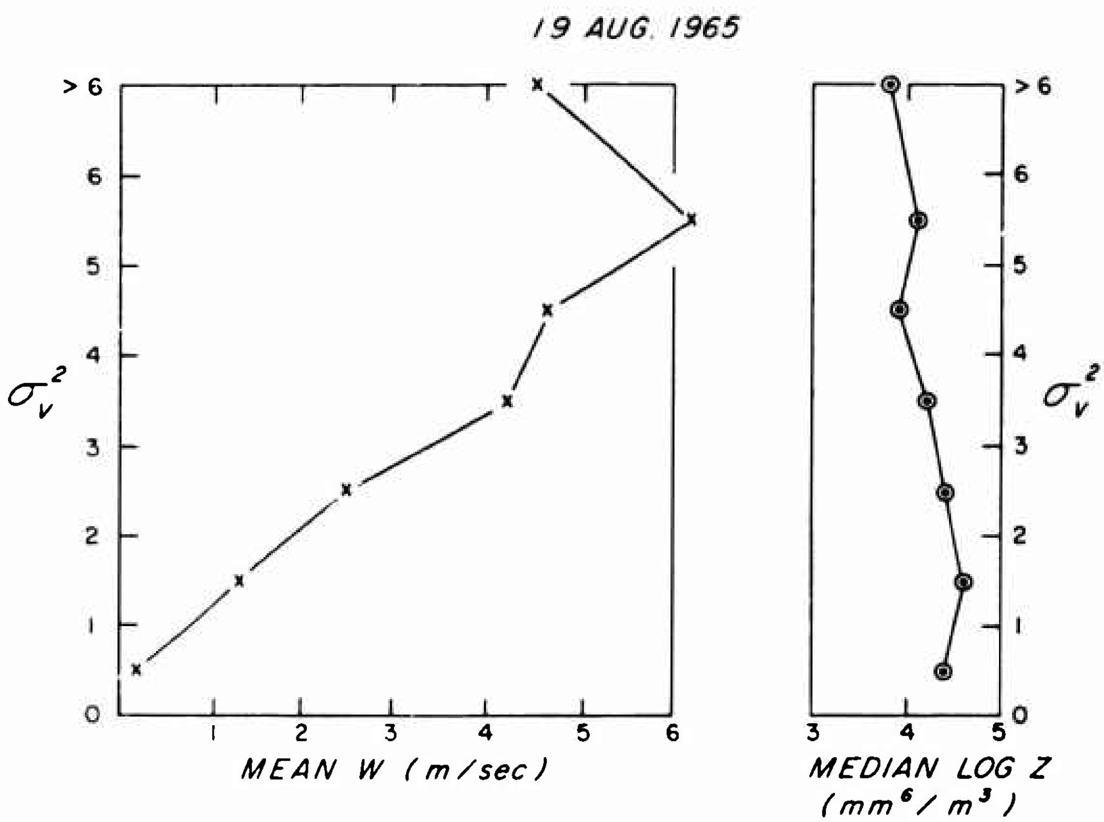

Figure 8. Relationship of Variance of the Vertical Velocity Spectra with Updraft Speed (left curve) and Radar Reflectivity Factor (right curve). The variance is grouped in seven categories (see text)

the spectral variance, while the Battan method is not. We conclude from Figure 8 that (1) spectral variance in our data is almost independent of reflectivity, with perhaps a slight negative tendency; (2) spectral variance, except for the highest values, is clearly associated with the magnitude of the updraft.

The correlation of spectral variance with the shear of the vertical wind is also positive and well defined. In Figure 9 the dotted line marked "horizontal" connects the median values, for each of the variance categories, of the horizontal shear of the vertical wind. Successive scans of the range gates at the same altitudes, spaced 27 seconds apart, were used in this computation. This time difference was converted to a horizontal distance of 500 meters, assuming little change in the vertical wind during the 27-second cycle, by estimating the storm speed through tracking small echo features with a different radar and by previous Doppler observation of the horizontal motion of the storm. Each computed value

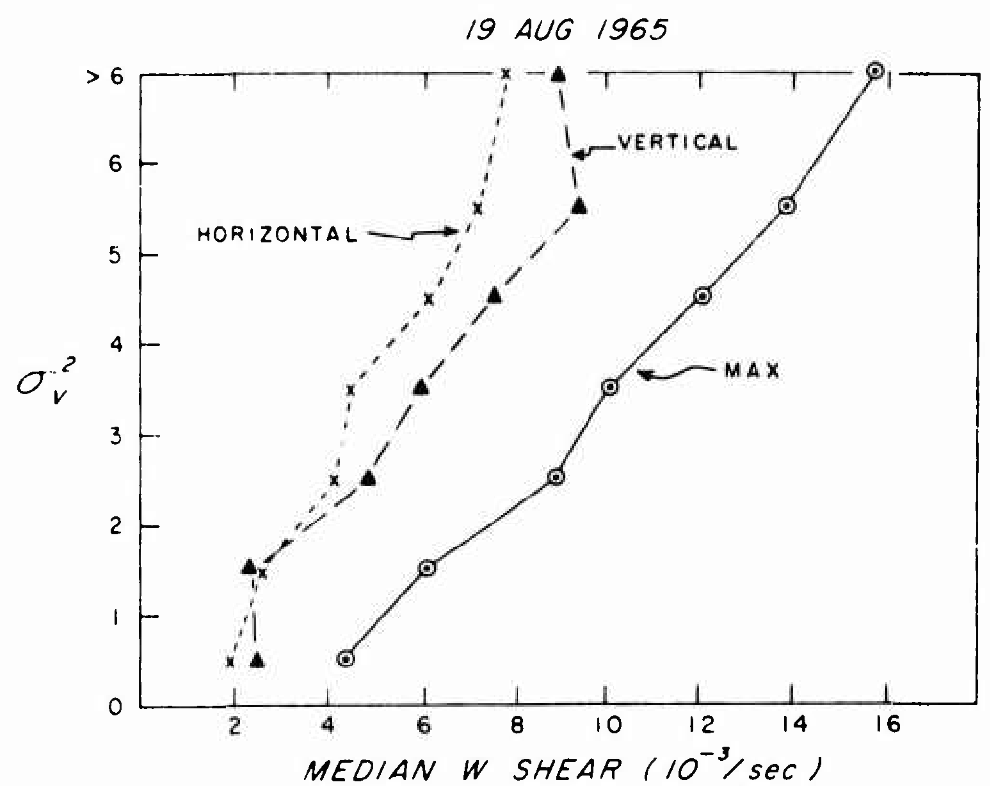

Figure 9. Relationship of Variance of the Vertical Velocity Spectra with Shear of the Updraft or Downdraft, with the Same Grouping Used in Figure 8. The line marked "max" relates variance at a point to the greatest shear in any direction about that point. The other lines relate horizontal or vertical shear of the vertical wind to the average spectral variance of the two points used in computation of the shear

of shear was associated with a value of spectral variance which was the mean of the two observations at the points involved in the estimation of shear. The dashed line marked "vertical" was derived in much the same manner. Here the vertical shear in the vertical wind was measured at the same time between adjacent range gates, a distance of 150 meters. The smaller distance over which the vertical shear was computed could account for its higher values.

The solid line marked "max" on Figure 9 represents the median of the largest value of updraft (or downdraft) shear in any of the four directions (up, down, right, or left) about a datum point, grouped according to the class interval of the variance measured at that point. This is a somewhat synthetic manner of examining shear, but it was done because of a feeling that the association between shear and variance might be nonlinear. Figure 9 does indeed indicate a very good correspondence between variance and the maximum computed value of shear.

Incidentally, the maximum values of shear measured in the 1965 Massachusetts thunderstorm were comparable to the values reported by Battan and Theiss (1966) in their 1963 Arizona thunderstorm. They reported a horizontal shear in vertical velocity of 5×10^{-2}/sec and a vertical shear of 2×10^{-2}/sec. Maximum values of the corresponding shears in the 1965 Massachusetts storm were 4×10^{-2} and 3×10^{-2}/sec.

Figures 8 and 9 indicate an independence or slight negative association of radar reflectivity with the variance of the vertical velocity spectrum, but a strong association of this variance with both magnitude and shear of the updraft. These relationships suggest that something besides the spread of precipitation fall speeds is contributing in a major manner to the higher values of variance. Since radar reflectivity is so sensitive to particle size, the small decrease of reflectivity with increasing variance in this storm does not support Battan's hypothesis that a large spread of vertical Doppler velocities is attributable mainly to the expansion of the particle size distribution to larger sizes and a greater range of fall speeds. (In two storms observed by Battan, however, in which reflectivity was well correlated with velocity spread, his hypothesis of a wide range of particle sizes is supportable.) Furthermore, large shear in the updraft would tend to sort the particle fall speeds regardless of the size of the largest particle. Therefore the large spectral variance observed in regions of large shear cannot be readily attributed to the existence of a broad particle size distribution. For these two reasons, whenever we see larger values of variance (perhaps anything above 4 m^2/sec^2) we might consider whether our spectrum has been broadened significantly by wind effects.

The three contributions to velocity variance by wind, as measured by radar, are (1) tangential wind components detected across the beam width, (2) wind shear along the beam, and (3) turbulence. The variances introduced by each of these processes are additive, since they are, to a good approximation, statistically

independent. Moreover, Hitschfeld and Dennis (1956) showed that they may all be fairly well represented by a Gaussian distribution of velocities. Also, Figure 7 shows that a Gaussian distribution is not a bad approximation to the great majority of velocity spectra observed in the 19 August 1965 storm.

The standard deviation attributed to tangential winds, derived by Hitschfeld and Dennis (1956), is $0.3\,\theta\,U_H$, where θ is half-power antenna beamwidth in radians and U_H is the tangential wind. The radar beamwidth is 1° or $\pi/180$ radians; the maximum tangential wind (for a vertical beam, this is horizontal motion) noted by Donaldson et al. (1966) was 20 m/sec. So the greatest standard deviation caused by tangential winds is $\pi/30$ m/sec, equivalent to a negligible variance of 10^{-2} m^2/sec^2.

The spectral broadening due to wind shear, however, is not negligible in many parts of the observed storm. Although shear of the horizontal wind is of no concern when the antenna is pointed at the zenith, the vertical Doppler velocity spectrum will be broadened somewhat by shear in the vertical wind. The radar pulse volume is longer in the radial, or vertical, direction within the height range encompassed by the observed thunderstorm, so the major contribution to shear variance is most frequently the vertical shear of the vertical wind. If the radar reflectivity is distributed uniformly with mean velocity along the region in which there is shear (that is, a square-wave Doppler spectrum), a given wind shear produces a maximum variance. For this form of the Doppler spectrum Lhermitte (1963) has computed a variance of $(\delta w)^2/12$, where δw is the total spread of velocity. The shear variance estimated in this manner will be an upper limit to the actual shear variance.

The median estimated shear variance was 0.15 m^2/sec^2 during the first three minutes of the storm of 19 August 1965. This was a region in which unusually high shear occurred in the updraft core near the leading edge of the storm, and also the region that contained the very large spectral widths which caused a discrepancy between the Rogers and Battan methods of estimating updrafts. In 13 percent of the region, however, the shear variance exceeded 1 m^2/sec^2, with a maximum value of 3.6 m^2/sec^2. Nevertheless, the shear variance contributed more than one-tenth to the total observed variance in only 30 percent of this region, leaving variance values as high as 19 m^2/sec^2 which must be attributed to a combination of particle fall speed distribution and to turbulence. Although Figure 9 demonstrates a good relationship between shear and the width of the velocity spectrum, it is apparent that shear alone is not able to account for unusually wide spectra. Therefore it is reasonable to expect that turbulence contributes to a major part of the spectral variance in certain regions of the storm. These regions of significant turbulence are located principally around the flanks of the leading updraft core, where $\sigma_V > 3$ m/sec (shaded areas of Figure 2) and the modified Battan technique for estimating particle fall speeds exceeds the modified Rogers technique by more than 4 m/sec (vertical hatching on Figure 6).

5. DISCUSSION AND CONCLUSIONS

It is possible, of course, that turbulent broadening of the vertical velocity spectrum is insignificant, as Battan and Theiss assumed, requiring a wide distribution of hail sizes (and fall speeds) to account for the large variance in vertical velocities observed in and around the leading updraft core. But I do not think that this is the case for the storm under discussion. A wide distribution in particle fall speeds would somehow have to survive the sorting tendencies of the coexistent large values of shear, which seems unlikely in view of the pronounced sorting of raindrop sizes reported by Battan and Theiss below their cloud base in a region of more gentle shear. Also, the slight negative association of reflectivity with spectral width in the Massachusetts storm, as illustrated in Figure 8, is at least suggestive that a wide range of velocities is not exclusively dependent on the presence of large particle sizes. Finally, it would seem appropriate that a variety of scales of wind variability should coexist near the edges of a convective updraft, and therefore it is not surprising that the observations suggest that large values of turbulence and shear in updraft speeds occur together.

In conclusion, the measurement of spectral width of vertical velocities appears to be a promising method for the detection of abnormally high values of cloudy-air turbulence. Furthermore, Battan's method of deducing vertical air velocities from the upper spectral bound may be inappropriate in the more active portions of thunderstorms, where turbulence and shear may broaden the velocity spectrum as much or more than the distribution of particle fall speeds.

This work is still in an embryonic stage, however. The following improvements are planned: (1) better analysis of the recorded frequency spectra in order to improve definition of the spectral width; (2) improvement in the relationship between reflectivity and mean particle fall speeds; (3) computation of the sorting effect of shear on model distributions of particle sizes; (4) extension of the analysis to other thunderstorms; and (5) observation at angles other than the zenith as an aid in separating the effects of wind and precipitation on the Doppler velocity spectrum.

Acknowledgments

I am grateful to Mr. Michael J. Kraus of Massachusetts Institute of Technology for performing, during his summer employment at AFCRL, the computations that were essential to this investigation. I am also pleased to acknowledge helpful discussions with Dr. Kenneth R. Hardy of AFCRL, and correspondence with Professor Louis J. Battan of the University of Arizona.

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Unclassified
Security Classification

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)* Hq AFCRL, OAR (CRH) United States Air Force Bedford, Massachusetts	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP -

3. REPORT TITLE

A Preliminary Report on Doppler Radar Observation of Turbulence in a Thunderstorm

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*

Scientific Report. Interim.

5. AUTHOR(S) *(Last name, first name, initial)*

DONALDSON, Ralph J. Jr.

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
January 1967	28	10

8a. CONTRACT OR GRANT NO.	9a. ORIGINATOR'S REPORT NUMBER(S) AFCRL-67-0015 ERP No. 255
b. PROJECT AND TASK NO. 6672-05	
c. DOD ELEMENT 62405394	9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*
d. DOD SUBELEMENT 681000	AFCRL-67-0015

10. AVAILABILITY/LIMITATION NOTICES

Distribution of this document is unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
	Hq AFCRL, OAR (CRH) United States Air Force Bedford, Massachusetts

13. ABSTRACT

Vertical-incidence observations by Doppler radar of velocities in a thunderstorm reveal some regions in which the spread of velocities is unusually broad. The widths of the vertical velocity spectra are generally greatest along the edges of a major updraft, where the maximum shear in updraft speed also occurs. The observations indicate that turbulence is an important cause of the abnormally wide velocity spectra, and suggest the utility of Doppler radar measurements of the vertical velocity spectrum as an indicator of severe cloudy-air turbulence. Furthermore, vertical velocity spectra in the more convective regions of thunderstorms, where they may be seriously affected by turbulence and wind shear, probably give an exaggerated picture of the particle size distribution.

DD FORM 1 JAN 64 1473

Unclassified
Security Classification

Unclassified
Security Classification

14. KEY WORDS	LINK A ROLE	LINK A WT	LINK B ROLE	LINK B WT	LINK C ROLE	LINK C WT
Doppler radar						
Thunderstorm						
Vertical velocity spectra						
Radar measurements						
Turbulence						
Wind shear						
Particle size distribution						

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